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Airborne Assessment of Methane Emissions from Offshore Platforms in the U.S. Gulf of Mexico

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ABSTRACT: Methane (CH_4) emissions from oil and gas activities are large and poorly quantified, with onshore studies showing systematic inventory underestimates. We present aircraft measurements of CH_4 emissions from offshore oil and gas platforms collected over the U.S. Gulf of Mexico in January 2018. Flights sampled individual facilities as well as regions of 5−70 facilities. We combine facility-level samples, production data, and inventory estimates to generate an aerial measurement-based inventory of CH_4 emissions for the U.S. Gulf of Mexico. We compare our inventory and the Environmental Protection Agency Greenhouse Gas Inventory (GHGI) with regional airborne estimates. The new inventory and regional airborne estimates are consistent with the GHGI in deep water but appear higher for shallow water. For the full U.S. Gulf of Mexico our inventory estimates total emissions of 0.53 Tg CH_4/yr [0.40−0.71 Tg CH_4/yr, 95% CI] and corresponds to a loss rate of 2.9% [2.2−3.8%] of natural gas production. Our estimate is a factor of 2 higher than the GHGI updated with 2018 platform counts. We attribute this disagreement to incomplete platform counts and emission factors that both underestimate emissions for shallow water platforms and do not account for disproportionately high emissions from large shallow water facilities.

INTRODUCTION

Leakage and venting of natural gas during extraction, production, processing, transport, and use of oil and natural gas is a large and uncertain source of atmospheric methane (CH_4).[1] Recent work examining CH_4 emissions from onshore oil and gas basins in the U.S. has consistently found discrepancies between official inventory estimates and atmospheric observations.[2] A contemporary estimate, revised with measurements collected from onshore production, processing, and transmission activities, suggests that U.S. CH_4 emissions for the natural gas supply chain are 60% greater than the U.S. Environmental Protection Agency Greenhouse Gas Inventory (GHGI).[2] This gap has been attributed to a combination of incomplete inventory counts of activity data (e.g., equipment counts),[3] incorrect emission factors (e.g., grams CH_4/activity),[2,3] and the presence of a few emission sources that are responsible for a disproportionately large fraction of emissions, termed *superemitters*.[3−5] A better understanding of CH_4 emissions associated with natural gas and oil is needed to both identify mitigation opportunities and evaluate the ability of natural gas use to reduce climate warming.[6]

Offshore oil and gas production is an important and understudied component of the oil and gas lifecycle. Global offshore production of crude oil and natural gas in 2016 amounts to 26.4 and 17.5 million barrels of oil equivalent per day,[7] which when compared to total production[8] represents 32% and 30% of the global total. Unlike onshore basins, oil, and gas platforms in offshore basins are often not expected to be large sources of CH_4 and have not been closely examined. This is in part due to the assumption that since platforms have high production rates, increased attention is paid to safety concerns from leaking CH_4.[9] Four studies have previously reported measurements of CH_4 emissions from offshore platforms, all derived from ship-based measurements. In the U.S. Gulf of Mexico, Yacovitch et al. (2020) show a skewed distribution of emitters from 103 sites, suggesting higher relative loss rates in shallow water than deep water.[10] In the North Sea, Riddick et al. (2019) found the cumulative loss rate from five directly measured platforms is nearly 50% higher than an inventory estimate.[11] However, Hensen et al. (2019) found that total emissions from 34 unique platforms appear consistent with reported emissions despite inconsistent platform-level emission rates.[12] In considering offshore platforms in Southeast Asia, Nara et al. (2014) suggested that the median emission rate derived from 14 plumes associated with platforms may be consistent with the inventory but showed that platform counts were underestimated.[13]

This study presents airborne measurements of offshore platforms in the U.S. Gulf of Mexico. The Gulf of Mexico outer continental shelf comprises 18% of U.S. oil production and 3% of U.S. natural gas production for 2017.[14,15] Platforms in the Gulf of Mexico are typically categorized as shallow water if the local bathymetry is shallower than ∼200 m[16,17] and deep water

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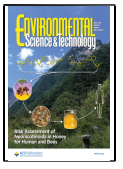

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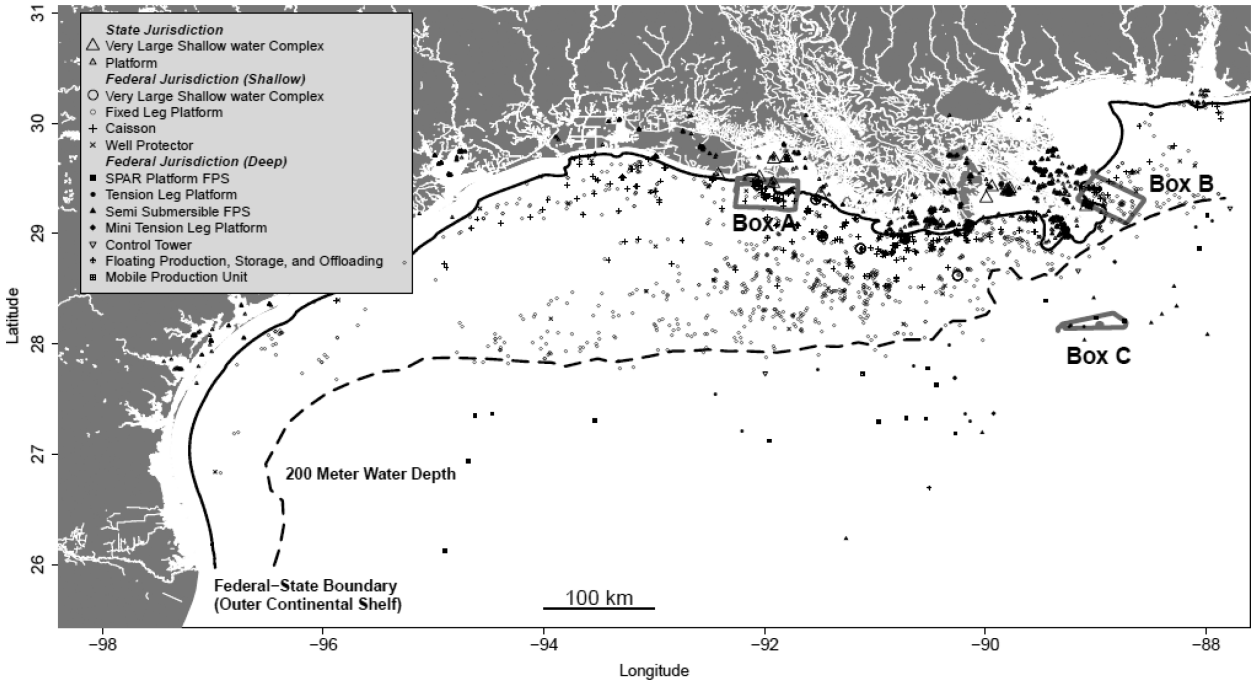

Figure 1. Map of the U.S. Gulf of Mexico offshore CH_4 aircraft campaign. Shown are aircraft tracks for three study sites (gray boxes), offshore platforms in federal waters reported in the 2014 GOADS and platform locations in state waters (small points), and the locations of the largest shallow water facilities (large points).

when located at greater depths. The shallow water Gulf of Mexico is primarily a historically developed natural gas basin with most of its proved reserves already produced and thus characterized by rapidly falling counts of active oil and gas platforms.[18] The deep water Gulf of Mexico is a recently tapped oil basin experiencing rising oil production as technological advancements have allowed for deeper and more extensive projects.[16,18] Generally, activities in deeper water require greater consolidation of operations relative to shallow water. While the infrastructure differs between offshore and onshore basins, oil and gas activities are similar. Drilling, production, processing, and transmission activities occur before hydrocarbons arrive onshore. See Supporting Information (SI) Appendix S1 for more information on the supply chain of oil and gas in the U.S. Gulf of Mexico.

We offer estimates of CH_4 emissions from offshore platforms under normal operating conditions derived from aircraft observations. Estimates are made from measurements of CH_4 collected during a U.S. Gulf of Mexico campaign in January 2018 at three regions shown in Figure 1: two in shallow water (Boxes A and B) and one in deep water (Box C). We quantify fluxes of CH_4 at two different scales using two independent methods. At the facility-level we use a cylindrical sampling technique (Figure 2a) and at the regional-level (5−70 facilities, totaling 5−154 platforms) we use horizontal transects to estimates the net flux of CH_4 out of a region (Figure 2b). We use the facility-level estimates, production data, and inventory estimates to develop an aerial measurement-based inventory that we then scale up to the regional-level for validation with the regional airborne estimates before scaling to the entire U.S. Gulf of Mexico basin.

MATERIALS AND METHODS

Aircraft flights were flown targeting Box A on January 17th and 18th, Box B on January 19th and 22nd, and Box C on January 23rd and 24th. Sites were chosen for a diversity of production and structure characteristics gathered from inventories and databases. We collected continuous in situ measurement of methane, carbon dioxide, carbon monoxide, water vapor, and ozone (SI Appendix S2). CH_4 measurements were made at a frequency of 0.33 to 0.5 Hz with a total uncertainty of 1.4 ppb.[19] In addition, we gathered observations of winds, temperature, and pressure (SI Appendix S2), and information on relevant platform and production data (SI Appendix S3). Facility-level fluxes are calculated for a total of 12 facilities randomly sampled in shallow and deep water using integrated molar fractions of CH_4 in rings cylindrically stratified above a facility[20] (SI Appendix S4). The approach has been successfully implemented to study various sources including sites in onshore basins[21,22] and dairy farms.[23] Regional estimates for each box are made using the mass balance equation on days and laps where we observe a developed mixed layer (SI Figures S1−S4 and Appendix S5). The technique has been widely used to calculate emissions, such as over onshore basins[24] and urban domains.[25] Emissions are estimated from the difference between the flux calculated from downwind transects and the flux calculated from upwind transects. Each lap flown around the box is treated as an independent sample and used in a Monte Carlo simulation to generate a mean and 95% confidence interval.

RESULTS AND DISCUSSION

Inaccurate Inventories. Current U.S. government inventories overestimate the number of oil and gas platforms in federal waters while missing platforms located in state waters. Two inventories offer emission estimates from platforms in the Gulf of Mexico: the GHGI and the Bureau of Ocean Energy Management Gulfwide Emissions Inventory,[26] generated using the Gulfwide Offshore Activity Data System (GOADS). Both inventories report emissions from platforms located in federal

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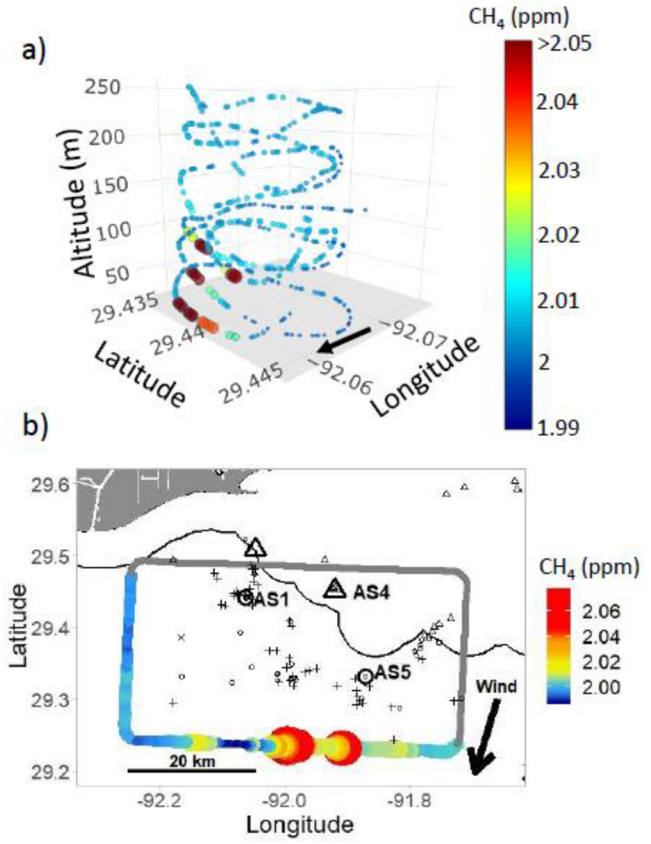

Figure 2. Aircraft tracks (lines), methane concentrations (color scale), and wind direction (arrows) for the facility-level measurements at site AS1 (a) and a downwind regional flux transect for Box A on January 17th (b). Points correspond to platform classifications described in Figure 1. The federal-state water outer continental shelf boundary is mapped. Data are used to estimate disproportionately high emissions from plumes on downwind transects related to sites AS4 and AS5.

waters on the outer continental shelf, which are nearly all located in the Gulf of Mexico. See SI Appendix S7 for further description of the inventories.

The current GHGI overestimates federal platform counts in the Gulf of Mexico. Federal platform counts have not been updated since 2010 (3490 in the Gulf),[27,28] despite much lower counts today (1800 in the Gulf and 30 in the Pacific as of August 2019 according to the Bureau of Safety and Environmental Enforcement (BSEE)[29]) due to rapidly falling production in shallow water.

The GHGI and GOADS inventories currently exclude platforms located in state waters. While waters under federal jurisdiction comprise the largest fraction of total U.S. offshore natural gas production (70% in 2017), platforms located in state waters contribute non-negligibly to total offshore U.S. gas production: 24% in Alaska state waters, 4% in Alabama state waters, 2% in Louisiana state waters, <1% in Texas state waters, and <1% in California state waters.[14] Figure 1 shows platforms in Texas, Louisiana, and Alabama state waters that are excluded from offshore inventories. We estimate that in total these may amount to over 1300 active facilities (SI Appendix S9). Although the EPA Greenhouse Gas Reporting Program does include facilities in state waters, there are only seven currently present in the Gulf of Mexico state waters. Platforms located in state coastal waters are presently missing in offshore and likely onshore federal inventories.

Identification of Platforms with Disproportionately High Emissions. We detect the presence of facilities with relatively high emission events of 790−3800 kg CH_4/h in both the facility and regional-level flights at sites AS1, AS4, and AS5 mapped in Figure 2b with emissions shown in SI Table S1. We classify these emissions as disproportionately high since they were at least a factor of 10 higher than the average emission rate from all other emitting platforms (61 kg CH_4/h) and dominate regional enhancements in Box A. During facility flights, two sites in Box A (AS1 and AS4) exhibited disproportionately high emissions that on two occasions exceeded the linearity regime threshold of 7000 ppb of CH_4 for the instrument onboard the aircraft, reaching values as high as 40 000 ppb. In addition, two large plumes are identified in regional flights in Box A which we relate to sources near AS4 and AS5 (Figure 2b and SI Appendix S6). AS5 was not individually sampled but identified later in the regional flights.

Disproportionately high emission events from these sites occur frequently. On the first day of flights in Box A, plumes associated with sites AS4 and AS5 on the downwind transects in Figure 2b were present on every lap around the box (~3 h). The second day of flights in Box A shows the presence of three large plumes on downwind transects (two laps over ~1.5 h). While the meteorological conditions on this day do not support further quantitative analysis, the plumes qualitatively appear consistent with sources near AS1, AS4, and AS5. The facility-level flights showed disproportionately high emissions from AS4 for two of 3 days sampled and AS1 on one of 2 days sampled (SI Table S1).

All facilities associated with disproportionately high emissions share similar characteristics concerning their role in the supply chain, size, and age. AS1, AS4, and AS5 are shallow water central hub facilities likely involved in processing and transmission of oil and gas. Throughput at these facilities may include transmission of deep water production to shore[16,18] (SI Appendix S8). Each facility is composed of a complex of platforms (between 7 and 16 platforms per facility). While many other central hub facilities are composed of multiple platforms, all facilities with seven or more platforms within our study sites showed at least one instance of disproportionately high emissions. Figure 1 shows the locations of the largest shallow water facilities in federal waters (those with seven or more platforms) and in coastal state waters (using satellite imagery). Large multiplatform shallow water facilities such as these are relics from when technology was insufficient to build vertical facilities.[18] We find that AS1 and AS5 include older platforms (SI Appendix S8). Old onshore oil and gas infrastructure combined with poor maintenance has previously been linked to high emission rates.[30]

It is unclear what activity is responsible for disproportionately high emissions. Equipment on AS1, AS4, and AS5 include storage tanks, compressors, dehydrators, amine units, and treaters. However, these are not consistent between sites or unique when compared to other central hub facilities. These facilities may have flares that are in operation some of the time. Combustion flares are considered a small CH_4 source in GOADS (<0.2%), but can make large contributions if the flare is inefficient[31] or not lit (and thus simply a vent). Flaring in the U.S. Gulf of Mexico is less predominant compared to offshore platforms in Mexican waters of the Gulf of Mexico.[32]

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Deliberate CH_4 release from vent stacks (cold venting) presents a plausible explanation (SI Appendix S8). Cold vent emissions follow bimodal variability and can be responsible for some of the largest emission events reported in offshore gas processing.[33] Venting is reported in federal waters following EPA guidelines but is unregulated[34] and has been linked to high concentrations of CH_4 responsible for numerous helicopter crashes.[34] In response to queries put to various industry companies, we have received daily input on some offshore wells, but none overlapped with large shallow water facilities.

While it is premature to identify the process(es) responsible, it is unlikely that we observed a rare phenomenon. High emissions may be released from nonroutine venting during a blowdown for equipment depressurization in maintenance operations associated with turnarounds or shut-downs.[35] However, if these events are uncorrelated between platforms, it is unlikely that such infrequent practices were present on all three sites (SI Appendix S8). Although there is some probability that flights sampled a rare high emission spike from another source of nonroutine venting, the probability of observing infrequent high emission pulses from multiple facilities on multiple days is low: we estimate less than 4% (SI Appendix S8). Previous work onshore has indicated that abnormal process conditions can contribute to a third of basin-level emissions.[36]

Disproportionately high emissions associated with the largest shallow water facilities do not appear to be fully captured by U.S. inventories. Inventories estimate relatively high emissions at these facilities due to higher equipment activity, by which GOADS scales, and platform counts, by which the GHGI scales. However, in comparison to the aircraft data the inventory estimates for sites AS1 and AS5 still appear too low: GOADS estimates 174 and 37 kg CH_4/h, while the aircraft estimates an average of about 1000 and 800 kg CH_4/h.

Facility-Level Emissions and Development of an Aerial Measurement-Based Inventory. Emission estimates made from the facility-level samples are shown in SI Table S1. For the 10 sites we find the facility weighted mean (median) emission rate is 373 (63) kg CH_4/h, excluding drill ships. If we exclude the influence of facilities with disproportionately high emissions we find 46 (36) kg CH_4/h. These findings are within the range of platform emission rates derived from ship observations: 18 (5) kg CH_4/h in the U.S. Gulf of Mexico (excluding drill ships),[10] 40 (24) kg CH_4/h,[11] and 23 (6)[12] in the North Sea, 61 (53) kg CH_4/h offshore Borneo,[13] and 449 (357) kg CH_4/h offshore the Malay Peninsula.[13]

A number of different categories of platforms with different rates of production were sampled (SI Table S1). Two relationships are identified that relate emission fluxes from producing platforms to (1) production and (2) platform complexity type. SI Figure S5 shows a negative power relationship (r^2 = 0.92) between the fraction of natural gas emitted to the atmosphere and the amount of natural gas produced per platform. Previous studies have also identified a negative relationship both onshore[2,24] and offshore.[11] This can be explained by relatively similar emission rates regardless of production.[24]

More complex platform types appear to have greater emissions that generally reflect the amount of equipment and level of activity occurring at the platform. We estimate zero emissions from small shallow water caisson platforms, low to high emissions for major fixed platforms in shallow water, and low to high emissions for deep water platforms (SI Table S1). This pattern is consistent with the way in which the equipment-level GOADS inventory is developed. SI Figure S6 shows that our emission estimates from producing and minor platforms tend to scale with the 2014 GOADS inventory, though significant discrepancies exist, with GOADS typically predicting lower emissions.

We develop a facility-level aerial measurement-based inventory to compare with regional-level airborne fluxes and estimate basin-wide emissions. The inventory is separated into three different source categories: (1) producing facilities, (2) nonproducing facilities (e.g., central hubs) and minor sources (caisson and well protector platforms), and (3) the largest shallow water facilities. CH_4 emissions from producing platforms are estimated using the relationship between the fraction of natural gas lost to the atmosphere and production per platform shown in SI Figure S5. We treat producing caisson and well protector platforms as nonemitting sources, since both the aircraft and GOADS inventory estimate negligible emissions from these minor platforms (SI Table S1 and Figure S6). For nonproducing platforms and minor sources, we rely on emissions reported by the 2014 GOADS inventory. This is in effort to include emissions from smaller central hub facilities and any pieces of equipment on caisson or well protector platforms. See SI Appendix S9 for further description of development and uncertainty of producing and nonproducing platform segments in our inventory.

We estimate average emissions from the largest shallow water facilities by combining a likely frequency and average emission rate for when disproportionately high emission events occur derived from samples in facility-level and regional-level measurements. We observed high emission events from facilities with seven or more platforms and assume that only the largest multiplatform facilities (also referred to as the largest shallow water complexes) are capable of high emission events. Platform count per facility does not reflect an understanding of the process, but does reflect the resolution to which these emissions are understood and correlates with factors that are typically predictive of emissions (age and amount of equipment).

The likely frequency is estimated using a binomial distribution generated from the number of occasions during which the aircraft sampled or was downwind of the largest shallow water facilities and observed disproportionately high emissions compared to the total number of possible occasions they could have been observed. We assign each 30 min interval of flight time per facility as one sampling occasion as this roughly reflects the sampling frequency of downwind transects on regional flights. Emission rates between transects (five transects flown over 3 h) do not show stark changes suggesting that emission rates may not change rapidly. Therefore, we treat facility-level samples, which were taken at a lower frequency of once per day per facility, as representative of 30 min. Enhancements associated with sources near AS1 on downwind transects in Box A appear related to multiple facilities and are treated as absent of disproportionately high emissions. We find that disproportionately high emissions are present ~70% ± 9% of the time (1σ). Next we calculate the emission rate for when disproportionately high emissions are present by combining the spread of disproportionately high emissions for each facility in a Monte Carlo simulation, with equal weighting between facilities (1600 ± 330 kg CH_4/h, 1σ). We calculate the average emission rate for the largest shallow water complexes to be

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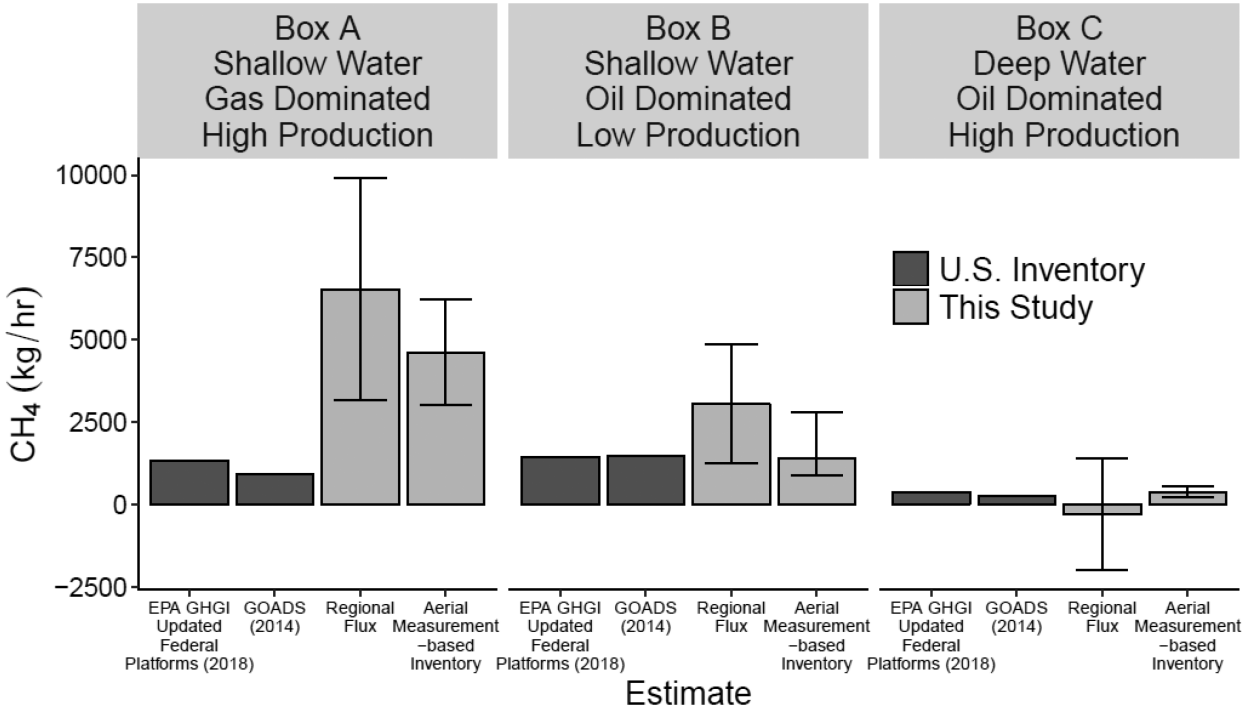

Figure 3. CH_4 emissions reported for Box A, Box B, and Box C by existing inventories, the regional flux, and the aerial measurement-based inventory. Mean and 95% confidence intervals (error bars) are shown.

1000 kg CH_4/h [600 to1700 kg CH_4/h, 95% CI] and apply it to facilities in federal waters with seven or more platforms (seven facilities) and platforms that appear active and very large in state waters as viewed from satellite imagery and aircraft photos (15 facilities).

Validation with Regional Fluxes. Figure 3 shows total emissions for all platforms in Box A, Box B, and Box C reported by U.S. inventories, the regional-level airborne estimates, and the aerial measurement-based inventory with 95% confidence intervals. Two U.S. inventories are shown: the 2014 GOADS and a spatially resolved GHGI estimate updated with 2018 federal platform counts (SI Appendix S7). Inventory estimates are scaled to hourly emission rates. The GHGI estimate is largely consistent with the GOADS estimate.

We attribute the bulk of regional-level fluxes to oil and gas platforms within the domain. The 2014 Gulfwide Emissions Inventory indicates that oil and gas platforms are responsible for the overwhelming majority of CH_4 emissions: 99.12% from oil and gas platforms, 0.02% from all support oil and gas activities, 0.04% from vessels not associated with oil and gas activity, and 0.82% from biogenic and geogenic sources.[26] Previous flights over the North Sea have warned that regional fluxes calculated from aircraft can contain land sources.[37] Our flights and analysis do not suffer from this limitation as we target individual facilities and regions and always sample upwind and downwind, isolating our region of interest.

Seepage of CH_4 at the seabed can occur in the Gulf of Mexico. However, ventilation to the atmosphere is limited given oxidation that occurs in the water column.[38] Our facility level flights, underlying this study, will not be sensitive to such a potential source. Regional flights could potentially be impacted. Therefore, we consider other tracers to identify air masses potentially impacted by ebullition events. We exclude from our calculation a lap in Box B with the presence of a unique CH_4 enhancement correlated with a sharp rise in specific humidity and strong draw down of CO_2. This could be a signature of an air mass impacted by ebullition, or possibly an air mass influenced by land which was not captured with upwind sampling.

Regional-level fluxes represent an aggregation of emissions from a diversity of platform types and production rates (SI Appendix S10). Total platforms sampled from the BSEE and state waters (from the 2014 GOADS in federal waters) were 154 (94) in Box A, 148 (83) in Box B, and 5 (5) in Box C. Note that some of these platforms are located within multiplatform facilities, not included in GOADS, and may be idle. We attribute most emissions in Box A to two plumes present during the full duration of regional flights (Figure 2b), and traceable to AS4 and AS5. Emissions in Box B are related to broad enhancements from many platforms (SI Figure S7).

Regional-level fluxes vary between the boxes. Emissions in the shallow water boxes appear higher than the deep water box. As a fraction of reported natural gas production, within the boxes, emissions in the shallow water boxes represent relatively high loss rates compared to deep water: 8% [4 to 12%, 95% CI] in Box A, 16% [6 to 25%, 95% CI] in Box B, and −0.2% [−1.1 to 0.8%, 95% CI] in Box C. Though the central estimate for Box C is slightly negative and the confidence interval includes negative values, we do not think this represents CH_4 uptake in this region, but instead is a manifestation of uncertainty due to significant variability in upwind CH_4 levels and relatively small observed downwind enhancements. It is possible that emissions associated with transmission of oil and gas volumes originally produced in deep water are released within the shallow water boxes, consequently increasing shallow water loss rates (SI Appendix S8).

Regional fluxes appear higher than government inventories for shallow water operations and within the uncertainty estimate in deep water. The mean regional estimates in the two shallow water boxes are at least a factor of 2 larger than the

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GHGI and GOADS estimates. In Box A, we attribute this disagreement largely to the emissions associated with large shallow water facilities. The GOADS estimate falls within the lower bound for Box B.

Similarly, the aerial measurement-based inventory trends higher in shallow waters compared to the U.S. inventories. While facility-level fluxes tend to scale with GOADS, samples of shallow water fixed platforms were higher than GOADS (SI Figure S6), and emissions from the largest shallow water facilities were underestimated by at least an order of magnitude.

The confidence intervals overlap between the regional fluxes and the aerial measurement-based inventory. This provides verification between regional-level estimates (calculated over ~250 platforms) and facility-level estimates of producing platforms (generated from a sample of six facilities and inventory data). This is not an entirely independent comparison for the largest shallow water facilities as the emission factor and frequency are calculated from a combination of facility-level and regional-level data. In shallow water, mean regional flux estimates are higher than our inventory. This may be due to biases in the regional flux estimates or missing emissions in the inventory we developed. In Box B, the mean emissions estimate in the aerial measurement-based inventory is consistent with GOADS and the skewed confidence intervals overlap with the regional flux estimate. The skewed distribution demonstrates the sensitivity of our inventory to emissions from fixed platforms with low natural gas production.

Comparison of U.S. Gulf of Mexico Emissions. We expand the aerial measurement-based inventory spatially to the full U.S. Gulf of Mexico (mapped in SI Figure S8) and temporally to an annual flux rate (justified in SI Appendix S10). SI Figure S9 shows that the frequency distribution of emissions, mean (21 kg CH_4/h), and median (3.4 kg CH_4/h) are very similar to sites sampled with ship-based measurements in February 2018 by Yacovitch et al. (2020).[10] In addition to evaluation with regional fluxes, this provides further support for the aerial measurement-based inventory.

Figure 4 compares total annual CH_4 emissions from oil and gas platforms in the Gulf of Mexico using current GHGI estimates made for 2010−2017,[39] a new alternative GHGI estimate made with updated 2018 platform counts (SI Appendix S7), the 2014 GOADS, and our 2018 aerial measurement-based inventory. We find that the GHGI with updated platforms would report ~0.22 Tg CH_4/yr, which is in agreement with the 2014 GOADS, and two-thirds of the 2010−2017 GHGI. This gap is due to lower platform counts in shallow federal waters in the Gulf of Mexico relative to 2010.

The aerial measurement-based inventory is most sensitive to emissions from the largest shallow water complexes. These facilities contribute to nearly 40% of the emissions, yet consist of <1% of total platforms. The uncertainty in cumulative emissions from these facilities is high and partly captured by our estimate of the spread in frequency and emission rate of disproportionately high emission events. However, we make two additional assumptions. First, we assume that our samples are representative of the whole year. Since the process(es) responsible are currently unknown it is impossible to ascertain whether this is true, but we proceed with the assumption since there is low probability of observing rare events on multiple platforms (see SI Appendix S8). Second, we estimate that a total of 22 facilities behave this way based on the assumption

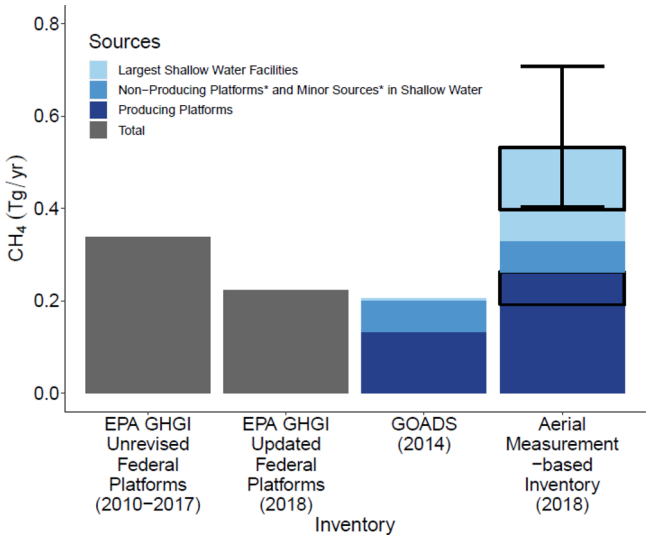

Figure 4. CH_4 emissions reported for offshore platforms in the U.S. Gulf of Mexico outer continental shelf (no borders) and state waters (borders) by existing inventories and the aerial measurement-based inventory. Mean and 95% confidence intervals (error bars) are shown for the aerial measurement-based inventory. (*) Signifies the estimate reported by this study is taken directly from the 2014 GOADS. Multicolored bars represent stacked bars.

that all facilities with seven or more platforms have disproportionately high emissions. It is likely that the phenomenon is not limited to or a characteristic of all large facilities. Any change in the count of facilities with disproportionately high emissions can rapidly change emission estimates. However, our frequency estimate negatively scales with our count of facilities and therefore moderates the influence of this assumption.

Cold venting presents a reasonable hypothesis for the disproportionate emissions observed here. If we assume this is the underlying process, a different scaling of observed disproportionate emissions is warranted given cold venting can lead to large instantaneous emissions but does not occur with great frequency. To consider this possibility and evaluate the impact on our basin-wide estimates, we can perform a new scaling by considering each facility with cold vents (502 in shallow federal waters) and assuming these facilities emit disproportionately high emissions as observed in this study for 2 days per year. This scaling would lead to 0.04 Tg CH_4/yr in federal waters, very similar to our estimate of 0.07 Tg CH_4/yr in federal waters based on the binomial aircraft observation frequency method that is agnostic to process.

The aerial measurement-based inventory is higher than current U.S. inventories, estimating total Gulf of Mexico emissions in federal waters and Texas, Louisiana, and Alabama state waters to be 0.53 Tg CH_4/yr [0.40−0.71 Tg CH_4/yr, 95% CI]. This is higher than the current GHGI estimate of 0.33 Tg CH_4/yr and over a factor of 2 higher than the GHGI with updated platform counts and the 2014 GOADS. The aerial measurement-based inventory is incomplete since it does not include emissions for nonproducing platforms in state waters, which were not isolated in aircraft measurements and are not recorded in existing inventories.

Three factors contribute to the discrepancy between our inventory and existing inventories. First, as outlined above, emissions associated with the largest shallow water complexes

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are considerably underestimated by current inventories (~400 kg CH_4/h in GOADS) compared to our aerial measurement-based inventory (~7700 kg CH_4/h in federal waters). Second, emissions from state waters are significant and presently omitted from inventories.

Third, emission rates from shallow water platforms are likely higher than current inventory emission factors. Figure 5

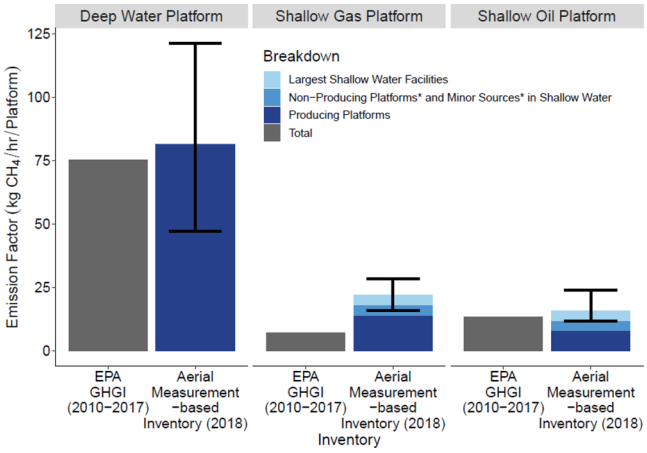

Figure 5. CH_4 emission factors aggregated into unique platform classes used by the current GHGI. Mean and 95% confidence intervals (error bars) are shown for the aerial measurement-based inventory. (*) Signifies the estimate reported by this study is taken directly from the 2014 GOADS. Multicolored bars represent stacked bars.

aggregates all emissions from federal waters in the aerial measurement-based inventory into emission factors that reflect the three unique emission factors used by the GHGI (see SI Appendix S11). While the deep water platform emission factor is the highest, shallow water platforms dominate platform counts in the U.S. Gulf of Mexico and therefore drive basin-wide emissions. Compared to the respective GHGI emission factors, the deep water emission factor appears consistent, but the mean emission factors for shallow water are higher. The shallow water gas platform emission factor is over a factor of 3 higher than the GHGI, with over half of the emissions from producing platforms alone. The current GHGI shallow oil platform emission factor falls within the lower bound of the 95% confidence interval of our inventory. However, the upper bound of the confidence interval is skewed and demonstrates that the emission factor could be up to 80% higher than the GHGI. The emission factor for shallow water−oil platforms is the most important in emission inventories as we estimate that over 75% of platforms in the federal and state Gulf currently fall into this category. Any revision upward can substantially increase basin-wide estimates.

Inventory underestimates of basin-level CH_4 emissions from offshore oil and gas activity may not be isolated to the U.S. Gulf of Mexico. Previous work has already shown the presence of incomplete activity data and possibly incorrect emission factors in other offshore basins.[11,13] We observe the presence of large shallow water facilities off the coast of Borneo with satellite imagery and note that the highest CH_4 emission rate estimates made to date were found by Nara et al. (2014) offshore the Malay Peninsula (650 and 1500 kg CH_4/h)[13] with a similar pattern to the disproportionately high emissions described in this study. It thus seems possible that platforms that contribute disproportionately to emissions are also present in other basins. Under-sampling of facilities with disproportionately high emissions can lead to underestimates of basin-wide emissions as previously noted in onshore basins.[2]

Our study shows that CH_4 emissions from offshore oil and gas activity in the U.S. Gulf of Mexico are not only underestimated, but also analogous to the highest emitting onshore basins. Total mean CH_4 emissions are comparable to emissions in the San Juan basin (0.54 Tg/yr)[41] and twice the emission rate of the Bakken (0.25 Tg/yr).[24] Production in the full U.S. Gulf of Mexico basin amounts to 3.0 billion cubic feet of natural gas per day,[40] similar in production to the San Juan basin.[2] As a fraction of total reported natural gas production, our estimate of offshore emissions represents a loss rate of 2.9% [2.2%−3.8%, 95% CI] assuming CH_4 represents 85% of gas volume. This is comparable to the average U.S. loss rate throughout the entire natural gas supply chain (2.3%)[2] and within the spread of mean loss rates from major onshore oil and gas basins, such the Marcellus in Northeast Pennsylvania (0.4%),[42] Haynesville (1.6%),[43] and Uinta (8.9%).[44] Typically, high loss rates are found in oil dominated basins, as found in Uinta and the Bakken (5.4%),[24] which is consistent with the emphasis on oil production in the Gulf of Mexico. A more granular evaluation of the aerial measurement-based inventory reveals that loss rates are quite high for both oil and gas dominated production in shallow water (6% in Box A and 7% in Box B) compared to deep water (0.2% in Box C).

To improve emission estimates and identify potential mitigation opportunities we recommend re-evaluating emission factors for shallow water platforms, particularly for large shallow water central hub facilities. Updating the GHGI activity data with new counts of platforms in federal and state waters, while an important correction, is not sufficient to accurately capture CH_4 emissions from oil and gas activity in the Gulf of Mexico. To match our observations, increases are needed to emission factors for shallow waters, and large shallow water central hubs must be accounted for. Adopting a facility-level production loss rate curve as we demonstrate here would be one approach to improve the inventory and produce an inventory that could be observationally evaluated and updated. We stress the need to understand the processes responsible for disproportionately high emissions and discern whether these emissions are related to transmission of gas from deep water production through these facilities, given projections of further expansion in deep water production.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c00179.

Additional background information, the complete methods (instrumentation, additional data, point source, and mass balance), and supplementary discussion (description of inventories, large shallow water complexes, the development of the aerial measurement-based inventory, justification for inventory expansion, and development of GHGI emission factors). Table S1 and Figures S1−S9 as referenced in text (PDF)

Aircraft data collected and used in this study are archived and available from the University of Michigan Deep Blue repository at DOI 10.7302/v559-6e13.

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A.M.G.N. and E.A.K. designed research; E.A.K., S.A.C., and M.L.S. designed data collection; S.A.C. and M.L.S. collected data; A.M.G.N, S.A.C, and M.L.S. analyzed data; A.M.G.N. performed research; E.A.K. advised research; A.M.G.N. and E.A.K. wrote the paper.

Notes

The authors declare no competing financial interest.

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